

## ABSTRACT

This invention teaches two new families of Si-based  $\text{Ge}/\text{Sn}_x\text{Ge}_{1-x}$  heterodiode and multiple quantum well (MQW) photonic devices: (1) *band-to-band* photodetectors, lasers, emitters, amplifiers and modulators for the 1.5 to 12  $\mu\text{m}$  wavelength range; (2) *intersubband* photodetectors, lasers, emitters and modulators for 12 to 100  $\mu\text{m}$  operation. The bipolar band-to-band devices have applications within the 1.5-2.2, 3-5 and 8-to-12  $\mu\text{m}$  bands. The unipolar intersubband group has longwave infrared and terahertz applications. All strained-layer devices are grown a relaxed  $\text{Sn}_y\text{Si}_z\text{Ge}_{1-y-z}$  buffer layer-- a virtual substrate (VS) grown directly upon a silicon wafer by unique LT UHV-CVD. The VS provides a low-defect atomic template for subsequent heteroepitaxy and is an essential enabling technique for engineering tensile and compressive strain within the  $\text{Ge}/\text{Sn}_x\text{Ge}_{1-x}$  MQW by selecting the VS lattice parameter to be approx midway between the layer lattices. Within alternating layers of the coherently strained MQW active region, the individual inplane strains are engineered to give a direct bandgap in the quantum wells and an overall strain balance in the stack (strain compensation). Strain balance with Sn content  $x \sim 2y$ , allows an unlimited MQW stack height as desired in most devices. An unsymmetric strain within the stack can also be engineered, although the strain-unbalanced-structures with their limited stack thickness have fewer applications. First-principles calculations predict that Type I band alignment is practical in the direct-gap strain-balanced case, while either Type I or II is feasible in the direct-gap unbalanced structures. This invention teaches practical

**embodiments of lasers, light-emitters, amplifiers, photodetectors and modulators that employ: (1) zone-center conduction-to-valence photon transitions involving electrons and holes in a device such as a PIN diode structure, or (2) zone-center  $\Gamma$ - $\Gamma$  intersubband photon transitions entirely between conduction subbands or between valence subbands. The NIN or PIP unipolar intersubband devices employ either electron or hole injection. For the 1.5-2.2  $\mu\text{m}$  band, the preferred embodiments are: the strain compensated MQW and simple 3-layer or 4-layer devices that are easy to manufacture.**